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Environmental Earth Sciences

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--Manuscript Draft--

Manuscript Number:	ENGE-D-16-02689R2
Full Title:	Shallow groundwater temperature in the Turin area (NW Italy): vertical distribution and anthropogenic effects
Article Type:	Original Manuscript
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Funding Information:	
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Response to Reviewers:	According to Editor's requirements the language of the paper has been revised by professional review's system American Journal Experts (AJE). See attachment (English review certificate by AJE)

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Manuscript title:

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Date Issued:

February 13, 2017

Certificate Verification Key:

9A83-E070-A35E-6880-689B

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Shallow groundwater temperature in the Turin area (NW Italy): vertical distribution and anthropogenic effects

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Keywords: groundwater temperature; thermal logs; seasonal oscillation; anthropogenic heat sources; ground-source heat pumps

Abstract

This study investigated the thermal regime of shallow groundwater in the Turin area (NW Italy), where the large energy demand has motivated a new interest for renewable sources, such as the use of ground-source heat pumps (GSHPs) for domestic heating and cooling. The vertical variability of the groundwater temperature between the ground surface and 10-20 m was detected: deeper temperatures were higher than shallow temperatures in spring, while a decrease with depth occurred in autumn. These variations are connected with the heating and cooling cycles of the ground surface due to seasonal temperature oscillation. Variations below the seasonal oscillation are likely to be connected with the presence of advective heat transport due to the groundwater flow, according to the hydraulic features of a shallow aquifer. Temperature values mostly ranged between 12°C and 14°C in rural areas, while below Turin city, the values were between 14°C and 16°C. This groundwater warming is attributed to a widespread urban heat island phenomenon linked to warmer land surface temperatures in Turin city. Sparse warm outliers are connected with point heat sources and site-specific conditions of land and subsurface use, which may cause the aquifer temperature to rise. A relatively stable temperature below the seasonal fluctuation zone combined with high productivity and legislated limits for deeper groundwater use represent favourable conditions for a large-scale diffusion of groundwater

heat pumps (GWHPs) within the shallow aquifer. Moreover, this heat surplus should be regarded as a resource for future geothermal installations.

1. Introduction

Italy still largely depends on non-renewable fossil fuels, despite its global energy goals for 2020. In particular, NW Italy is a highly populated and industrialized area where large conurbations (Turin, Milan) present critical issues for the large energy demand. Geothermal energy, one of the most promising renewable worldwide sources, has had limited development in the country in terms of electricity generation in recent years. Medium to high enthalpy geothermal sources accounted for 1.8% of the national gross energy generation in 2005 (European Commission 2007), and the total contribution to the final energy consumption, excluding geothermal heat pump applications, decreased from 213 to 130 ktoe/year (toe=tonne of oil equivalents) in the period of 2009-2014 (European Commission 2015). High and medium enthalpy geothermal sources for electricity generation have had limited development in NW Italy, hence, alternative green sources should be used. Furthermore, domestic heating and cooling needs, which could possibly be provided by low enthalpy heat, represent a relevant fraction of fossil fuels consumption in the northernmost regions. For these reasons, low temperature geothermal reservoirs are being increasingly regarded as promising thermal energy supplies. Recently, geothermal systems have doubled their contribution to the final consumption of renewable energy in Italy from 39 to 71 ktoe/year, but this amount still represents a small part of the national demand of 10,000 ktoe/year for thermal energy (European Commission 2015). Geothermal systems operation is based on the heat exchange between the soil and the groundwater and a heat pump. This procedure requires knowledge of many thermal and hydraulic properties, including the undisturbed subsurface temperature, thermal conductivity, groundwater occurrence, local flow direction, groundwater level depth, and recharge conditions (Stauffer et al. 2013). The undisturbed temperature is a crucial parameter because it represents the base thermal energy level that can be extracted/injected by a geothermal heat pump. In a closed-loop system (GSHPs, ground-source heat pump), the heat-carrier fluid circulating into the vertical heat exchanger acquires the undisturbed temperature of the subsurface, whereas an open-loop system (GWHP or groundwater heat pump) operates via a direct exchange between the groundwater and the heat pump; hence, the aquifer temperature is the same as the inlet temperature.

In NW Italy, the availability of shallow groundwater resources in the Po Plain makes the area very promising for the large-scale dissemination of geothermal heat pumps, for example, for use in district heating (Sparacino et al. 2007; Beretta et al. 2014) and space heating (Baccino et al. 2010). Furthermore, large cities are typical cases because previous studies indicate that a heat surplus is expected to occur beneath an urban area (Ferguson & Woodbury 2004; Zhu et al. 2010; Menberg et al. 2013).

The Turin area still lacks a city-scale thermal aquifer characterization despite recent advances in geothermal applications. The present study is concerned with the temperatures of the shallow groundwater in the Turin area. Data were collected in both urban and rural areas adjacent to the city, and their distribution was related to both regional and local factors, for example, the climatic regime, land use, and aquifer recharge and discharge. The effect of anthropogenic warming was reported and some preliminary considerations about the future dissemination of GSHPs in the Turin area have been expressed according to the survey results.

2. Temperature model

The shallow underground temperature regime is mostly determined by the air temperature. The unsaturated zone is the first part of the subsurface to be reached by an external input. The temperature of this zone can be described using a 1D heat diffusion model for a semi-infinite solid if approximations are made, i.e., a homogeneous medium with no vertical water movement. Water input due to infiltration from the ground surface can be considered negligible in a heat transfer process because it is of short duration in well-drained sites (Taylor & Stefan 2009). The solution to the diffusion model, provided by Banks (2008), among others, consists of temperature variations with time and space around the average ground temperature T_m. This value represents the topmost boundary value, and it is transient because the air temperature is subject to daily and seasonal variation. T_m is difficult to determine since it depends on the way the air temperature is transmitted in the topmost soil. The T_m is generally higher than the air temperature (Stauffer et al. 2013), but measurements of this parameter are very infrequent; hence, the air temperature is commonly used as the approximate temperature at the ground surface. The subsurface temperature variations mainly depend on the amplitude of the temperature oscillation at the ground surface, which depends on the local climate and land cover conditions. Furthermore, an exponential term gives the decay of temperature fluctuation with depth, and a cosine term provides the cyclicity of the increasing time lag with depth. In general, these variations show that more oscillation penetrates into the ground during longer temperature cycles, but the amplitude is gradually damped with depth by the heat dissipation within the geologic medium. For instance, Silliman and Booth (1993) reported that the amplitude of the temperature is not significantly affected by diurnal fluctuations at the ground surface below 1.5 metres.

The depth interval affected by external temperature oscillations can be designated as the "surficial zone", and it precedes the so-called "geothermal zone" in which a constant increase in temperature occurs due to the geothermal gradient (Anderson 2005).

Physical processes become more complex when surface seasonal inputs reach the shallow groundwater and a 2-layer model better describes the temperature distribution (Taylor & Stefan 2009). The thermal conductivity is enhanced because the pores and fractures are now filled, replacing air and giving continuity to the geologic medium. At the same time, the high heat capacity of the water causes a reduction of the heat diffusivity. In aquifers with high permeability, the flow velocity of the water in the porous medium, the inertial effects and eventual turbulence increase the apparent thermal diffusivity until it is orders of magnitude greater than the molecular thermal diffusivity (Taylor & Stephan 2009). This phenomenon results in an increased rate of heat transport due to the hydrodynamic effects of the horizontal and vertical water movements. Such phenomena lead to temperature distortions below the surficial zone and above the geothermal zone. Alterations in the thermal regime can be traced by borehole temperature measurements in recharge and discharge sectors as concave or convex profiles, respectively (Taniguchi 1999; Anderson 2005). Multi-temporal borehole measurements in very shallow aquifers are useful to assess cyclical temperature variations. Generally, these observations lead to flower-shaped profiles followed by constant temperature values. Taniguchi (1993), among others, provides type-curves for assessing the recharge and discharge regime depending on whether it has an elongated or compressed shape. The constant temperature below the surficial zone with seasonal oscillations is usually 1 to 2°C higher than the average annual temperature at the ground surface (Anderson 2005).

However, the groundwater temperature can be assumed as relatively constant throughout the year in comparison with the seasonal air oscillations typically recorded in a medium temperate climate of Europe. Consequently, most part of aquifers can be used as low enthalpy geothermal reservoirs, compensating for the daily and seasonal delay between need and supply of heat and cold (Rybach & Eugster 2010).

The amplitude of the temperature oscillation in aquifers strictly depends on the local climate and land use, as previously shown. The shallow groundwater is thus necessarily affected by anthropogenic factors at various scales. The most evident thermal footprints occur beneath urban areas because local climate conditions, land use changes and artificial heat sources are concentrated there. Temperature increases of several degrees have been recorded in the urban subsurface all over the world, including in Asian megacities (Taniguchi et al. 2007; Zhu e al. 2010) as well as German (Menberg et al. 2013) and Finnish cities (Arola & Korkka-Niemi 2014). The primary cause has been identified as the replacement of natural land cover by artificial surfaces and heat loss from buildings. The magnitude of the temperature increase due to anthropogenic land use varies depending on the type and density of the heat source. For instance, Taylor and Stefan (2009) observed increments of up to 3°C linked to isolated roads. Menberg et al. (2013) expressed the urban heat island intensity as the difference between rural and urban areas, finding values between 1.9°C and 2.4°C in some German cities. However, warmer temperatures indicated by borehole measurements have also been linked to global warming (Taniguchi et al. 2007, Bayer et al. 2016). A specific analysis of past climate signals is required to distinguish the two overlapping phenomena.

A synthetic scheme has been reported (Fig. 1) to summarize those anthropogenic heat sources that are expected to occur in the investigated area to discuss them along with the results. The idea of a schematic conceptual model of heat sources that affect the groundwater temperature in an urban area was first contributed by Menberg et al. (2013) and further elaborated by Benz et al. (2015). Since the Turin area includes both rural and urban sectors, the sketch includes the most representative heat sources for both land use types. Point, linear and areal sources can be distinguished using geometrical criteria. In rural areas (left side of Fig. 1), natural land use prevails, even though some anthropogenic sources with both areal and linear geometry can be found, such as irrigation and canals (1). In this case, the input can be either colder or warmer depending on the type of water source (river, aquifer, etc.) and on the cultivation. Point sources are those elements that have small dimensions, for example, sewage systems (2) and isolated buildings or roads in remote areas (3), landfills (4), industrial sites (5), and wells for thermal wastewater reinjection such as geothermal wells (6). Linear sources include many types of underground infrastructures such as sewage systems or district heating networks (7) and railway and road tunnels (8). Benz et al. (2015) provide evidence that sewage systems play a dual role in higher ground and groundwater temperatures, as exemplified by the heat loss from pipe walls and warm water leakage from damaged pipes. Areal sources are large built-up areas (9), where the previously mentioned point and linear sources (roads, buildings, sewage systems, etc.) occur at high density and extension and, for instance, heat losses derived from elevated ground surface temperatures caused by interconnected asphalt and paved surfaces.

3. Study area

3.1. Climatic context

The area investigated is located in NW Italy and includes both the narrow sector of the western Po Plain between the Western Alps (W) and Turin Hill (E) and the internal plain sector of the Ivrea Morainic Amphitheatre (Fig. 2). At the regional level, the climate is determined by an orographic component rather than by latitude because of the presence of the Alps and the small latitudinal development of the region (Agenzia Regionale per la Protezione Ambientale 2007). Air temperatures show a regular decrease with elevation and are sporadically changed by local conditions such as urban areas or valley floors. In plain areas, the average annual temperature is between 10°C and 12.5°C, with higher average monthly values in autumn than in spring.

Temperatures are also subject to the effects of global climate change. An analysis of a historical climate series (Cortemiglia 1999) shows an increase of 0.8°C per century in the plain areas of the Piedmont region. The average annual value increased from 12.5°C to 13.7°C during the periods of 1870-2010 and 1971-2010 (Garzena et al. 2014). Furthermore, in the Turin area, the air temperatures in the city were higher than in surrounding rural area throughout the 20th century because of an urban heat island phenomenon (Oke 1995, Voogt 2004). Such a rise in temperature over the last 150 years is likely to be caused by the vigorous expansion of the city. The increase in the number of inhabitants and vehicles in Turin city are among the largest and are responsible for the urban air warming according to Garzena et al. (2014).

3.2. Geological and hydrogeological context

A synthetic geo-hydrological map (Fig. 2) depicts the main lithological features of the area, which include the metamorphic rocks of Western Alps (1), Tertiary marine and transitional deposits (2), and Quaternary glacial deposits (3) that form morainic amphitheatres at the outlets of main Alpine valleys. The metamorphic rocks and Tertiary deposits merge underneath the Po Plain sediments, forming a weakly permeable bedrock. Transitional to marine units deposited in the Pliocene and early Pleistocene are found above the bedrock and consist of silty-clayey levels interbedded with sands and gravels. The Po Plain was formed by Quaternary outwash and fluvial units (4) consisting of heterogeneous sediments, mainly sands and gravels with subordinated silty and clayey levels (Festa et al. 2009; Forno et al. 2009; Irace et al. 2009). The oldest sediments are discontinuously distributed and include highly weathered soils, while the youngest sediments are ubiquitous and less altered. The distribution of the Quaternary units is linked with the morphology of the Po Plain, which has been conventionally divided into two sectors known as the high and the low plains. The high plain is located at the uppermost elevations near the Alps and was formed by the oldest sediments (middle Pleistocene), while the low plain is located topographically at lower elevations and comprises late Quaternary and Holocene deposits.

From a hydrogeological point of view, the sediments of the Po Plain represent a continuous highly permeable porous medium that hosts many groundwater systems. Conventionally, one shallow and various deep aquifers have been described (Bortolami et al. 1988; Bove et al. 2005; De Luca et al. 2014). The deeper aquifers are hosted in the sandy intercalations of transitional and marine deposits found below the continental units. They are multi-layered, and their groundwater circulation is confined to the sandy levels. The recharge of the deep aquifers occurs in the high plain sectors, where the units outcrop or the low permeable intercalations have limited spatial continuity and thickness. Early Pleistocene sediments with low permeability vertically separate the deep and the shallow groundwater systems. The shallow aquifer is hosted in late Pleistocene and Holocene units and it is mostly unconfined. The shallow aquifer is supplied by the infiltration of rainfall and secondarily by rivers in the high plain sectors. The low plain sectors are generally discharge areas and the Po River represents the main regional discharge axis for the groundwater flow (Debernardi et al. 2008; Lasagna et al. 2016a, b). The regional flow is thus directed from the Alps towards SE-E-NE (Fig. 3). The water table generally follows the topographic surface trend, and its depth varies between 1 and 50 metres, with minima in the high plain sectors. The hydraulic gradient varies between 0.1 and 3% with higher values in high plain sectors.

3.3. Geothermal context

The geothermal manifestations in the Piedmont region are limited to sporadic cases of hydrothermal circuits with local significance in the SE (Acqui Terme, see for example Pasquale et al. 2011) and the SW Piedmont (Vinadio and Valdieri, see Perello et al. 2001 and Baietto et al. 2008). The most promising and easily accessible reservoir of low enthalpy heat is currently represented by the Po Plain (Lo Russo et al. 2015). Both shallow and deep aquifers may be exploited within the typical depths of low enthalpy geothermal systems, according to the previously described lithostratigraphic setting. Closed systems cross both the shallow and the deep aquifers, while open systems are mostly associated with shallow aquifers. The use of deep aquifers is protected by regional regulations, which restrict deep groundwater withdrawal only for human consumption and limit drillings that cross two aquifers. Hence, the focus of the many geothermal investigations has been on the shallow aquifer. Recent studies (Stringari et al. 2010) assessed the shallow aquifer temperatures in the Po Plain at regional scale. The average annual the groundwater temperature is approximately 14°C, but lateral variability reaches several degrees Celsius. A positive temperature gradient occurs from the SW to the NE Piedmont along the regional groundwater flow direction and locally from the high plain to the low plain sectors. Such lateral temperature variations have been attributed to both regional climatic trends and hydrogeological features, including the heat conduction from the ground surface in progressively warmer climatic conditions and the thermal equilibration of colder rainfall waters infiltrating recharge areas (high plain) with warmer subsurface along the groundwater flow path towards the Po River.

4. Methods

One of the most common techniques in thermal groundwater characterization at both shallow and deep depths (Taniguchi 1993; Taniguchi et al. 1999) is the downhole thermal log. It can be performed by automatic acquisition or manually, for example, by thermal resistances equipped with wires of the proper length (Barbero et al. 2016). In this study, the groundwater temperatures were collected in two surveys, one performed in spring and one performed in autumn, that consisted of downhole thermal logs performed manually. Temperature values were recorded throughout the entire water column by an electronic water level metre equipped with a thermometer (0.01 m and 0.1°C sensitivity). In the spring survey, 40 monitoring points were used, and 30 wells were used in the autumn survey; most of them were managed by the regional Environmental Protection Agency (ARPA). Since Turin city lacks ARPA monitoring wells, supplementary points owned by private authorities were included in the measurements (Table 1). The depths of the wells ranged between 8 and 50 metres and were screened exclusively in the shallow aquifer. The following two classes of land use were distinguished: rural and city. The city type included the wells within the municipal boundaries of Turin, and the rural type encompassed the remaining areas.

Table 1 Information about monitoring the well design, site features and the groundwater temperature data. The latter are divided into S (the spring survey) and A (the autumn survey). (*Well top temperatures are meant to be the first useful measurement, namely 1 m below the groundwater level.)

Code	Land use	Elevation	Depth	Screens penetrating the whole water column	Groundwater level		Saturated thickness		Well top temperature*		Well bottom temperature		Temperature difference within water column (Ttop - Tbottom)	
					S	A	S	A	S	A	S	A	S	A
		(m a.s.l.)	(m b.g.l.)		(m b.g.l.)	(m b.g.l.)	(m)	(m)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)
Arpa P43	rural	229	23	No	3.56	3.98	19.44	19.02	13.5	14.2	12	13.1	1.6	2.9
Arpa P42	rural	254	25	No	5.50	6.65	19.5	18.35	13.5	13.5	12.3	12.3	1.7	2.1
Arpa P45	rural	384	42	No	23.57		18.43		13.5		13.4		0.2	
Arpa P24	rural	301	35	Yes	24.05	22.95	10.95	12.05	14.0	14.1	13.6	13.7	0.6	0.6
Arpa P38	rural	259	50	Yes	47.22		2.78		13.2		13.2		0	
Arpa P20	rural	237	20	No	2.38	3.01	17.62	16.99	13.7	16.0	14.4	14.5	-1.7	4.2
Arpa TF2	rural	233	15	No	5.70		9.3		13.7		13.6		0.1	
Arpa P16	rural	238	25	No	5.45		19.55		15.3		14.8		0.6	
Arpa PZ-SL6	rural	279	20	No	4.75	5.14	15.25	14.86	13.2	18.5	13.4	18.3	-0.3	0.35
Arpa P15	rural	299	30	Yes	22.67		7.33		12.4		12.3		0.1	

Arpa P3	rural	196	30	No	7.29		22.71		13.6	13.3	13.3		0.4	
Arpa PZ-SL3/1	rural	330	20	Yes	8.52	8.89	11.48	11.11	13.2	13.3	13.1	13	0.8	0.6
Arpa P18	rural	275	30	No	25.87	25.91	4.13	4.09	13.8	13.9	13.7	13.8	0.1	0.1
Arpa PZ-SL5/3	rural	274	20	No	13.57	15.07	6.43	4.93	13.8	14.1	13.8	14.15	0.1	-0.05
Arpa P19	rural	226	35	No	3.87	4.20	31.13	30.80	16.4	17.1	17.9	18	-2.4	-0.7
Arpa PZ-SL1	rural	441	15	No	3.26		11.74		10.3		12.3		-3.3	
Arpa PZ-SL7/1	rural	252	20	No	3.36		16.64		12.8		13.6		-2.4	
PZC1	rural	225	30	Yes	4.49	4.87	25.51	25.13	15.2	16.4	15	14.9	0.1	2.3
PZ10	rural	247	8	Not known	0.95	1.20	7.05	6.80	12.0	15.4	13.7	14	-2.9	2.2
Orbassano P1	rural	262	23.5	Not known	11.04	11.68	12.46	11.82	14.5	14.4	13.9	14	0.9	0.5
Arpa P10	rural	274	25	Yes	14.16	12.15	10.84	12.85	13.1	14.3	12.7	14	0.7	0.4
Arpa P22	rural	238	15	No	0.00	1.12	15	13.88	14.7	14.7	14.7	14.6	-3.1	5.4
Arpa P21	rural	266	20	No	2.67	3.65	17.33	16.35	12.3	15.3	13	13.5	-1.7	3.1
Arpa P37	rural	208	22.5	Yes	19.39		3.11		12.1		12.2		-0.1	
Arpa PZ-SL4	rural	319	20	No	1.41		18.59		13.0		13.9		-1.8	
Arpa P17	rural	258	14	No	1.12	1.95	12.88	12.05	13.3	15.9	13.3	13.3	-2.7	4.8
Arpa P44	rural	232	25	No	7.50	7.82	17.5	17.18	13.6	13.4	13.4	13.4	0.3	-0.1
S nuovo	city	223	13	Not known	5.51	4.86	7.49	8.14	14.8	16.6	15.5	15.2	-1.4	2.5
PZ N1	city	224	15	Not known	6.36	6.60	8.64	8.40	15.7	15.7	15.8	15.7	-0.2	-0.1
Arpa SI2	city	218	20	Yes	7.66	7.92	12.34	12.08	15.7	15.6	15.8	15.2	-0.3	0.5

PZ B3	city	257	35	Not known	26.31	26.55	8.69	8.45	15.1	14.9	15	14.9	0.1	0.05
GTT PM2	city	270	40	Yes	33.79	33.91	6.21	6.09	14.3	14.2	14.2	14.2	0.1	0.1
PZ34	city	240	40	No	17.42		22.58		19.7		15.5		7.8	
PZ50	city	265	40	Yes	18.21	18.39	21.79	21.61	14.7	14.7	14.5	14.5	0.4	0.5
Arpa P26	city	247	42	No	21.49	21.80	20.71	20.40	14.9	14.9	14.8	14.9	0.2	0
PZ55	city	270	45	Yes	38.22	38.34	6.78	6.66	14.2	14.2	14.1	14	0.1	0.2
Arpa P30	rural	263	35	No	15.72	16.47	19.28	18.53	14.5	14.3	14.5	14.25	0	0.05
Arpa SI5	rural	177	20	Yes	9.65		10.35		14.6		14.4		0.3	
Arpa PZ-SL2	rural	380	20	No	2.95		17.05		9.0		9.2		-0.4	
Villarbasse P1	rural	337	14	Not known	10.18	10.64	3.82	3.36	12.8	12.7	12.7	12.6	0.1	0.2
Arpa P7	rural	246	15	No	2.05	2.38	12.95	12.62	12.3	13.1	12.8	12.8	-1.4	2.8
Arpa P34	rural	218	20	No	3.12	4.08	16.88	15.92	11.3	13.9	12.2	15.7	-2	1.6
Mean			25.53								13.8	14.4		
City mean											15.0	14.8		
Rural mean											13.4	14.2		

5. Results and discussion

The vertical distribution of the groundwater temperatures assessed by the thermal logs shows lower values in the shallow portions and a gradual increase in the spring measurements (Fig. 3). Conversely the values are higher in the first few metres and decrease with depth in autumn (Fig. 4). This vertical temperature variability is compatible with the heating and cooling cycles of the ground temperatures due to seasonal variation. According to the previously described heat transfer processes, the external daily and seasonal fluctuations are damped in the subsurface by the heat dissipation occurring in the unsaturated zone and in the shallow portions of aquifers. In the shallow wells, the temperature variations disappear within 10-20 metres below the ground surface. In the deeper wells (<20 m), the temperature variations are smaller. In the shallow wells, the attenuation occurs in the aquifer, enhanced by the groundwater flow. In the deeper boreholes, the inputs from the ground surface are dissipated into the unsaturated zone above the groundwater table. This phenomenon was confirmed by the good correlation between the depth to the groundwater and the temperature difference along the water column (Fig. 5). The plot also shows that the decrease in the temperature difference is particularly rapid at <10 m the groundwater level depth.

In both the spring and autumn logs, the deeper portions of the aquifer show small temperature oscillations and a constant value ranging between 12°C and 15°C is reached in most wells, which is compatible with the presence of the groundwater flow in the aquifer, as reported in Taniguchi's (1993) shallow borehole thermal logs. Recent studies on the groundwater temperatures in the Piedmont Po Plain (Stringari et al. 2010; Barbero et al. 2016) suggest that in the shallow alluvial aquifer, a homoeothermic surface to distinguish where the groundwater temperatures are constant in time should be defined, that is, where the daily and seasonal oscillations are no longer evident. The homoeothermic volume is the aquifer volume below the homoeothermic surface and above the geothermal zone in which the geothermal gradient causes a temperature rise. The homoeothermic surface for the whole Piedmont Po Plain ranges between 20 and 25 metres b.g.l. according to Barbero et al. (2014), and this range is compatible with the analysis of the thermal logs reported in this study (Fig. 3 and Fig. 4).

The vertical variations in the aquifer were considered before extracting a single temperature value for each well. For this purpose, the well bottom measurements were considered as representative of the aquifer temperature. The values were between 9.2°C and 17.9°C in spring and between 12.3°C and 18.3°C in autumn (Table 1). The well top measurement of each log was used to compute the difference along the entire water column (Table 1). Negative values (i.e., colder temperatures in the uppermost part of the aquifer) correspond to the spring logs according to the shape of thermal logs described above. Conversely, the values are mostly positive in the autumn logs because shallow temperatures are warmer. The overall temperature variation range in the monitored wells in both surveys is between -2.9°C and +5.4°C (excluding one outlier in the spring survey, which will be clarified later).

The bottom temperature measurements extracted from thermal logs were plotted on maps to distinguish lateral variations of the aquifer temperature excluding the seasonal temperature variations. The spring temperature values (Fig. 7) mostly lay in the interval of 12°C-14°C in rural areas. Some cold outliers below this range were found N of Turin city in the high plain sectors close to the Alps. In Turin city, the aquifer temperatures were generally higher (14°C-16°C), while the three easternmost wells had intermediate values (14°C-15°C). In the autumn survey (Fig. 8), the spatial distribution was approximately the same, with occasional warmer values. The average values across the investigated area were 13.8°C and 14.4°C in spring and autumn, respectively, and reflected minor variations between the two surveys. These temperatures were very close to the average annual air temperatures recorded in the Piedmont Po Plain, according to the aforementioned climatic features. Temperatures gradually increased from the high plain sectors close to the Alps towards the Po River, which matched the main groundwater flow direction. Colder aquifer temperatures in the high plain sectors reflected the colder top soil temperatures occurring in the sectors close to the Alps well, due to the cooling of the air with an increase in the topographic elevation. This effect was confirmed by the correlation between the groundwater temperatures and the well elevation (Fig. 6). This groundwater warming along the flow path was found by several basin-wide studies. Stringari et al. (2010) found this trend in the Piedmont Po Plain, as described in section 3.2. Burns et al. (2016) found a similar increase in the land surface and the groundwater temperatures along the Eastern Snake River Plain aquifer (SE Idaho, US). The same authors also reported that the thickness of the unsaturated zone had the primary effect of insulating the aquifer from the land surface. A similar observation is also valid for the Turin Po Plain in the present study: wells with a deeper groundwater level have narrower temperature oscillations (Fig. 5; Fig. 7; Fig. 8). Cooler groundwater in the high plain sectors may also be partially determined by inputs from surface hydrology; in the high plain sectors, the rivers and streams generally feed the aquifer, while in the discharge areas, the aquifer is drained by the rivers. The different hydrogeological role of the respective recharge and discharge areas of the high and low plain sectors of the Turin Po Plain is not still clear. The role of recharge and discharge sectors was reported to have major importance in determining the shape of the thermal logs of the shallow aquifer in the Nagaoka area by Taniguchi (1993). In the present study, such a distinction would benefit from a comparison of the temperature logs derived from the two distinct hydrogeological areas.

The high concentration of warm temperatures below Turin city is likely linked to the presence of the large urbanized area. A rough estimate of the intensity of the groundwater warming below the city was made by comparing the urban and rural bottom well (i.e., undisturbed) temperatures (Table 1). The results showed warmer average temperatures in the city monitoring wells of +1.6°C and +0.6°C in spring and autumn measurements, respectively. The difference between the two surveys may be affected by extrinsic factors, such as the smaller number of points considered in the second survey. More than one phenomenon acting simultaneously in the urban areas may cause groundwater warming, i.e., global warming and the urban heat island effect. In Turin city, an urban heat island effect in the air (see Paragraph 3.1) likely affected the temperature of the shallow aquifer. The magnitude of the urban air warming during recent decades was similar to the warming in the aquifer. In addition, a long climate series analysis indicates that global climate change exists (see Paragraph 3). Unfortunately, deeper borehole temperatures are not available to distinguish past climate signals in the groundwater; it can only be stated that further studies should take into account its recent transitory behaviour. Indeed, Garzena et al. (2014) found that during 1992-2009, the urban heat island decreased in intensity, as evidenced by the relatively constant average annual air temperature in Turin city; however, it increased in rural areas. Another type of heat source with a linear geometry is expected to have an effect on a city scale: old and largely damaged wastewater networks are distributed across the subsurface of Turin, and extensive leakage is expected to be found.

Most wells have been drilled close to roads, squares and buildings. Paved and asphalt surfaces modify the porosity and reflectivity of the natural soil, causing an enhancement of heat accumulation at the ground surface (Taylor & Stefan 2009), while buildings increase the temperature of the surrounding subsurface via their foundations, basements or underground car boxes (Menberg et al. 2013). Local warming due to artificial land use is thus expected to contribute in both rural and urban areas. However, the longer history and larger size of Turin city make this phenomenon much more intense with respect to the surrounding urban centres.

Sporadic outliers have been found that can scarcely be explained by the previously mentioned phenomena. Positive local temperature anomalies are generally related to single point heat sources, for example, industrial districts, power stations, and landfills, that can affect a small subsurface volume. One of these points lies outside Turin city in the S sector (La Loggia) and has a high temperature (>17°C). This anomalous warming is likely linked to the presence of an industrial district that may be responsible for an abnormal heat flux from the buildings due to the huge volumes of warm air inside and/or to industrial exothermic processes. Another outlier is represented by a well in Turin city which showed anomalous temperatures (up to 23°C) in the spring thermal log (Fig. 3). This anomaly is easily explained by the presence of a geothermal system working in heat injection mode. Two outliers in the towns of Volpiano and Caselle showed marked differences between the two surveys (3°C to 5°C, respectively). Such values indicate that the seasonal effect was probably not completely excluded. Without prior knowledge of localized heat sources, the limited depth of the groundwater and the presence of large paved parking areas next to the monitoring point might have amplified the heat accumulation during the warm months. Furthermore, the points at the southern boundary of Turin city show higher temperatures (14°C-15°C range) compared with the points at the northern side of the city. One of these points is located close to the town of Moncalieri. Since this well is used for monitoring a polluted site, the exothermic decomposition of organic compounds may have affected the temperatures of the subsoil and aquifer. This monitoring point should be further investigated to better understand how the anthropogenic factors in the area, mainly at the contaminated site and secondarily of the paved surfaces, may affect the thermal regime.

6. Conclusions

The scenario outlined shows that the regional climatic trend largely influences the thermal regime of the shallow aquifer in the Turin area. A seasonal oscillation can be clearly recognized, and it is rapidly damped in the shallow portions of subsurface. In addition, other factors also play an important role, such as the recharge conditions and anthropogenic contributions. The latter could be distinguished in the thermal regime of the shallow aquifer either as a diffuse temperature increase due to Turin city or as local differences linked to local heat sources, such as polluted sites, industrial districts, or geothermal systems.

However, the current thermal trend of the shallow aquifer in the Turin area shows a relatively stable temperature, since the seasonal oscillations only affect the shallow portion of the aquifer. This phenomenon, combined with high productivity, contributes to the creation of favourable conditions for large-scale diffusion in the shallow aquifer for heat pumps coupled with the groundwater (GWHPs). At present, the installation of GWHPs is limited; however, an increasing demand for domestic heating and cooling by means of this technology may lead to a rise in conflicts. The findings of this study would then represent a contribution for the future sustainable development of GWHPs in the Turin area. For instance, the heat surplus identified in the urban area could be used as a resource for building/district heating. This strategy should be accompanied by further efforts to gain new knowledge about the thermal features of shallow aquifers as affected by both local and regional factors, for instance, by extending the monitoring network to the Turin subsurface. New temperature data to better support site-specific interpretations may be collected and, once combined with hydraulic parameters such as saturated thickness, transmissivity and storage, could be used to compute the potential for GWHP exploitation in a sector such as an urban area. However, such large-scale characterization should not exclude a detailed site-specific assessment of hydrogeological and thermal properties for new installations.

Acknowledgements

Most of the groundwater monitoring points were accessed thanks to the kind support of Arpa Piemonte and Provincia di Torino. The authors are grateful to all collaborators as well as to all the private institutions and individuals who permitted access to other monitoring wells. The authors deeply thank the reviewer for useful comments and suggestions that helped to improve the paper.

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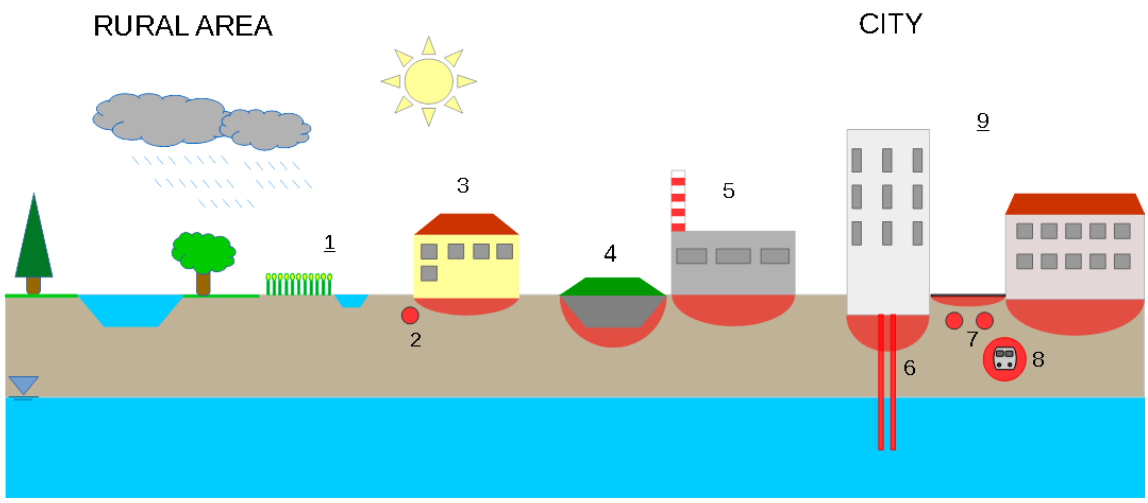

Fig. 1 The ground surface anthropogenic inputs that affect the temperature in shallow aquifers in rural and urban areas. Areal sources are distinguished by an underlined number.

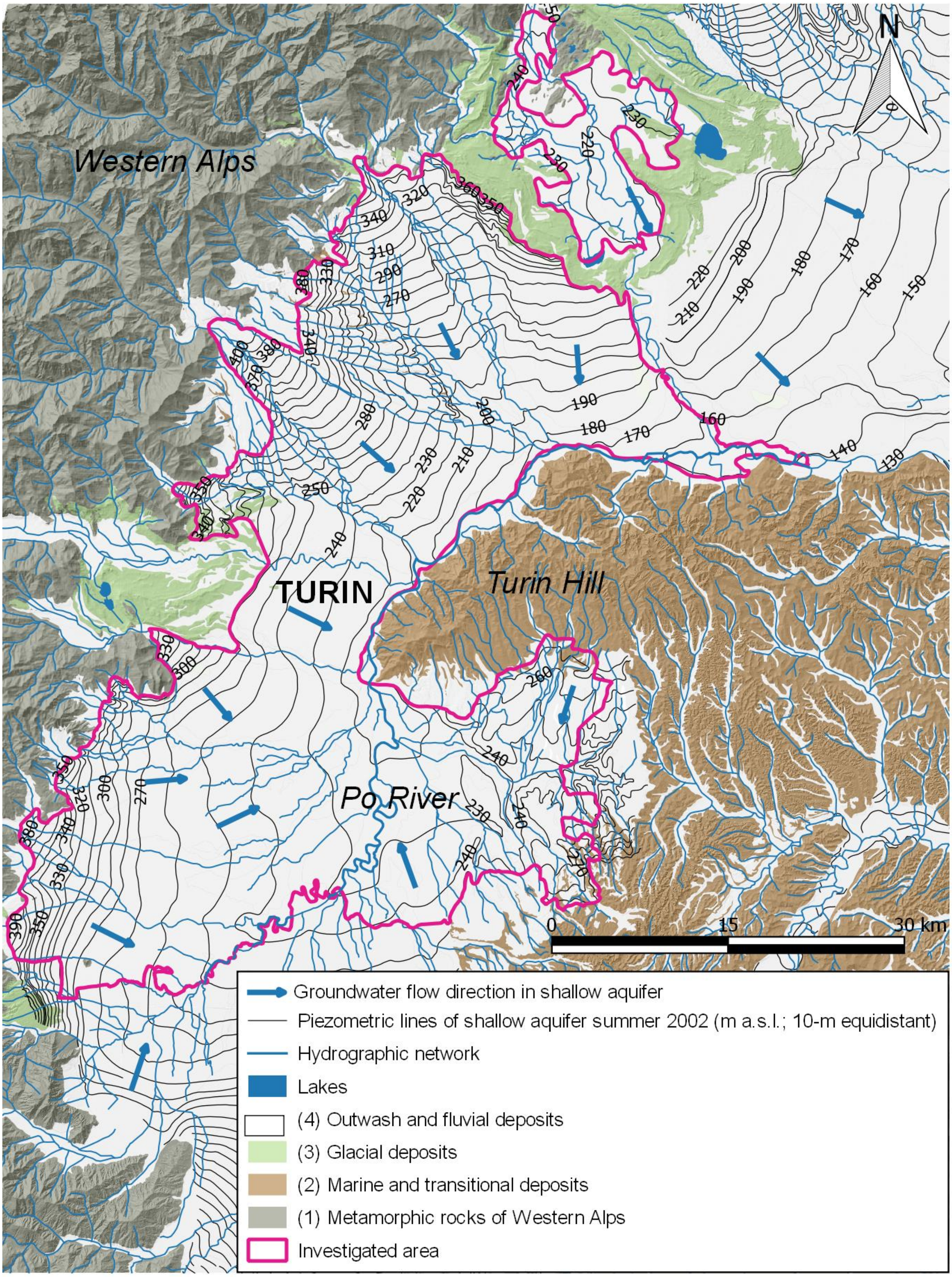

Fig. 2 Geo-hydrological map of the area investigated.

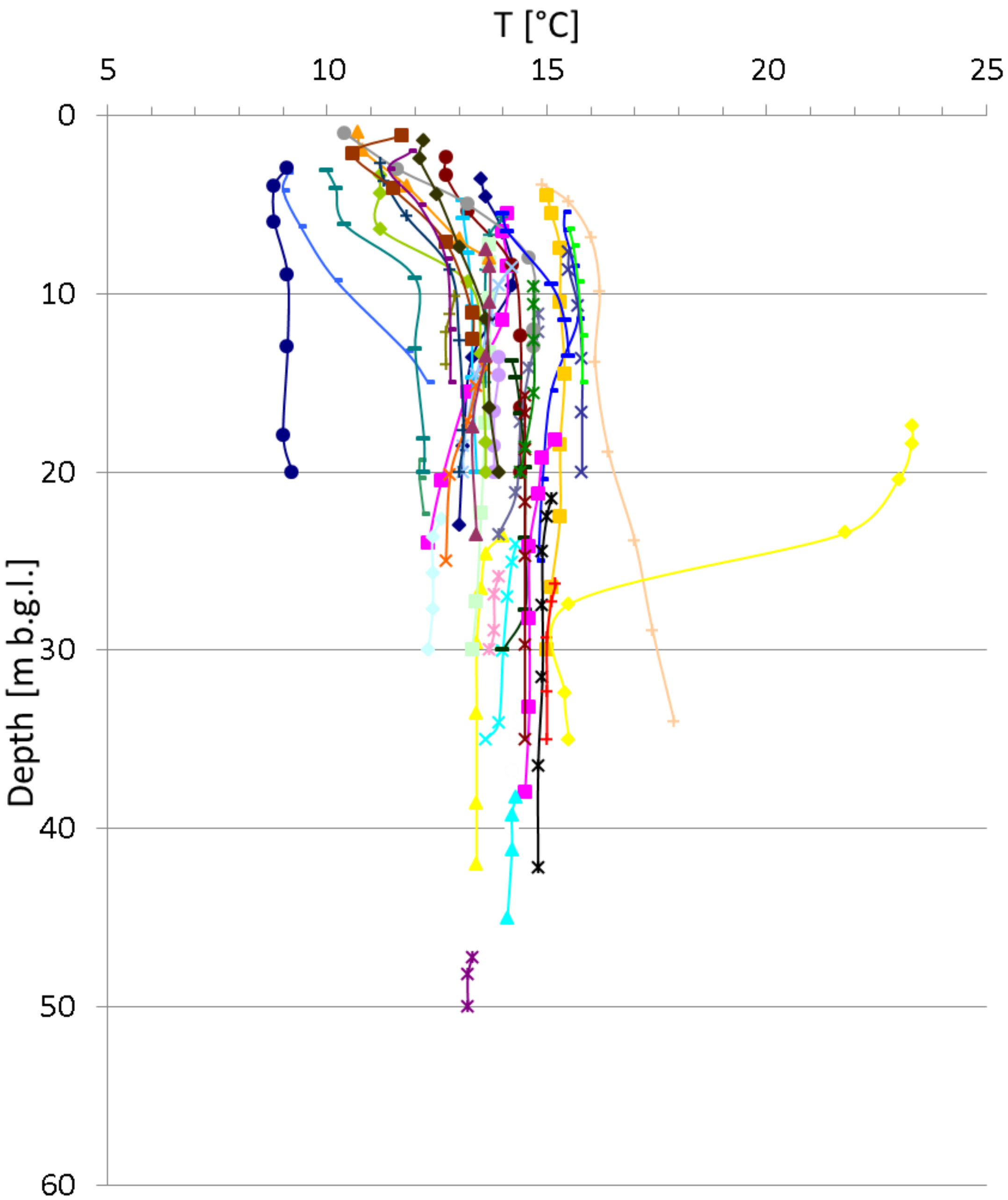

Fig. 3 Temperature logs recorded in the spring of 2014.

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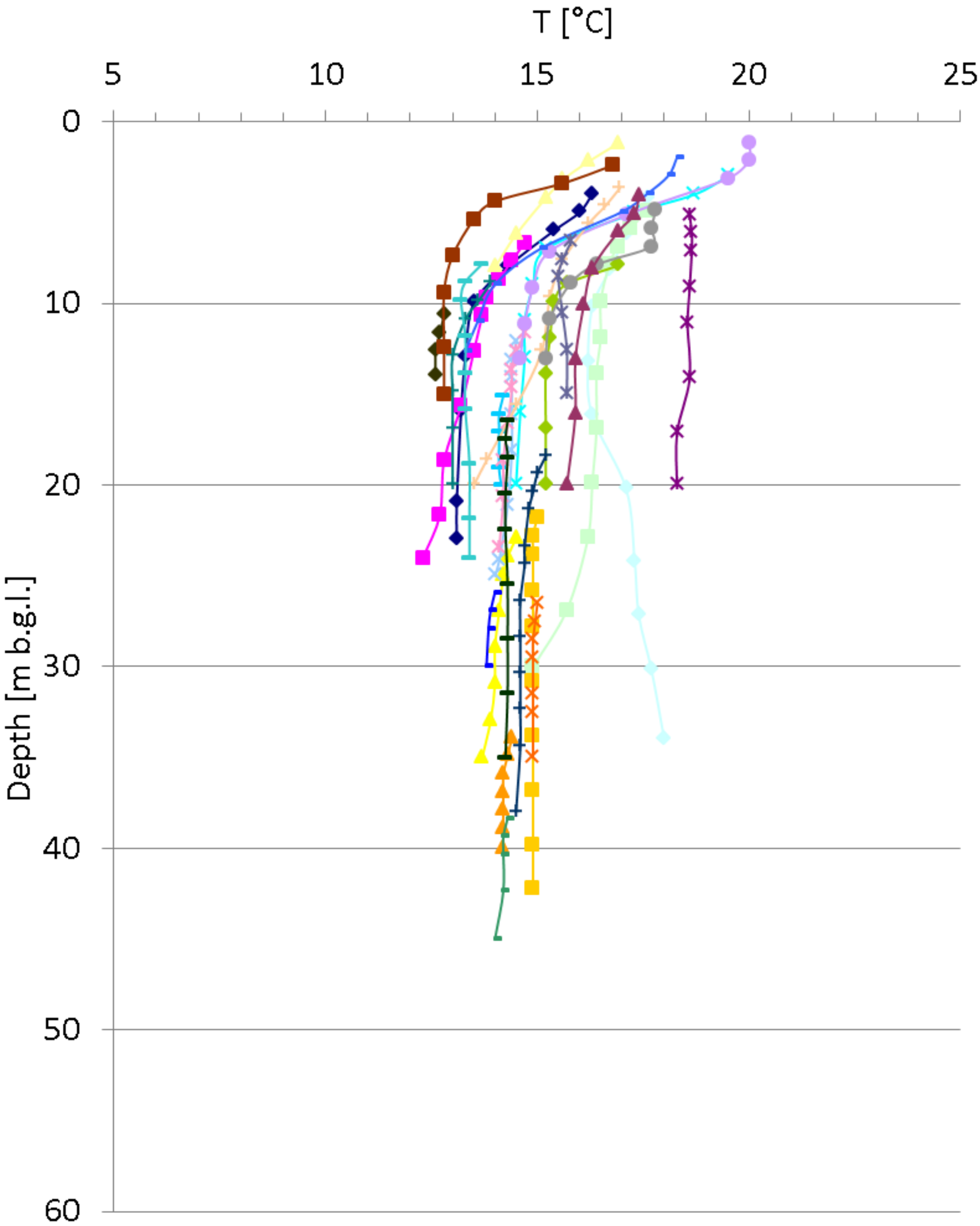

323 **Fig. 4** Temperature logs recorded in the autumn of 2014.

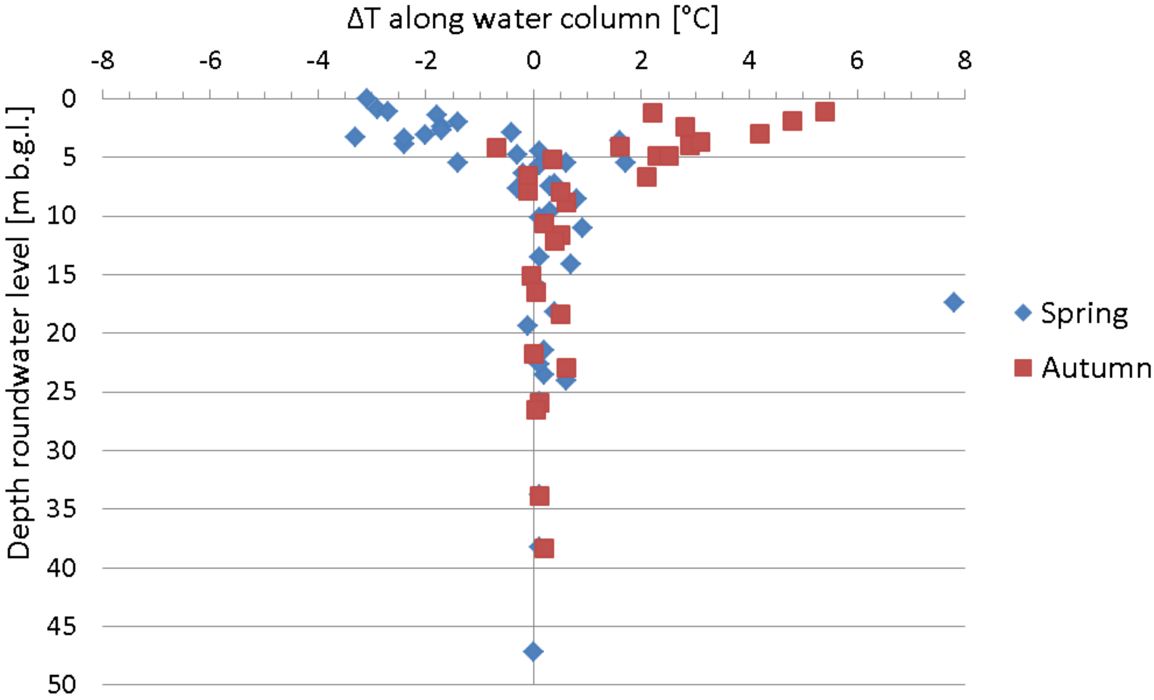

Fig. 5 The groundwater temperature correlation with temperature difference along water columns in the wells.

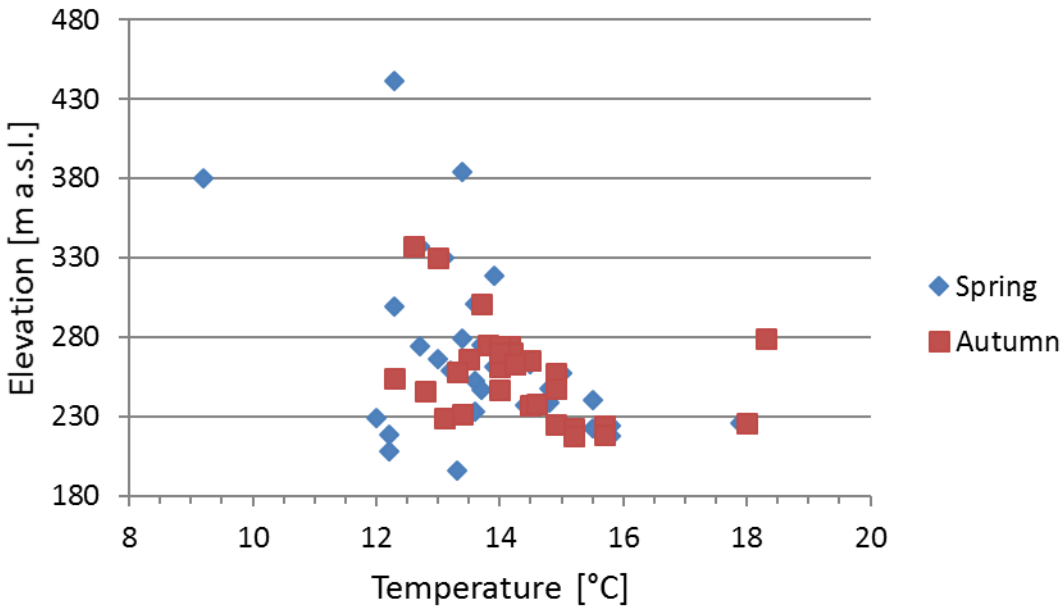

Fig. 6 The groundwater temperature correlation with well elevation.

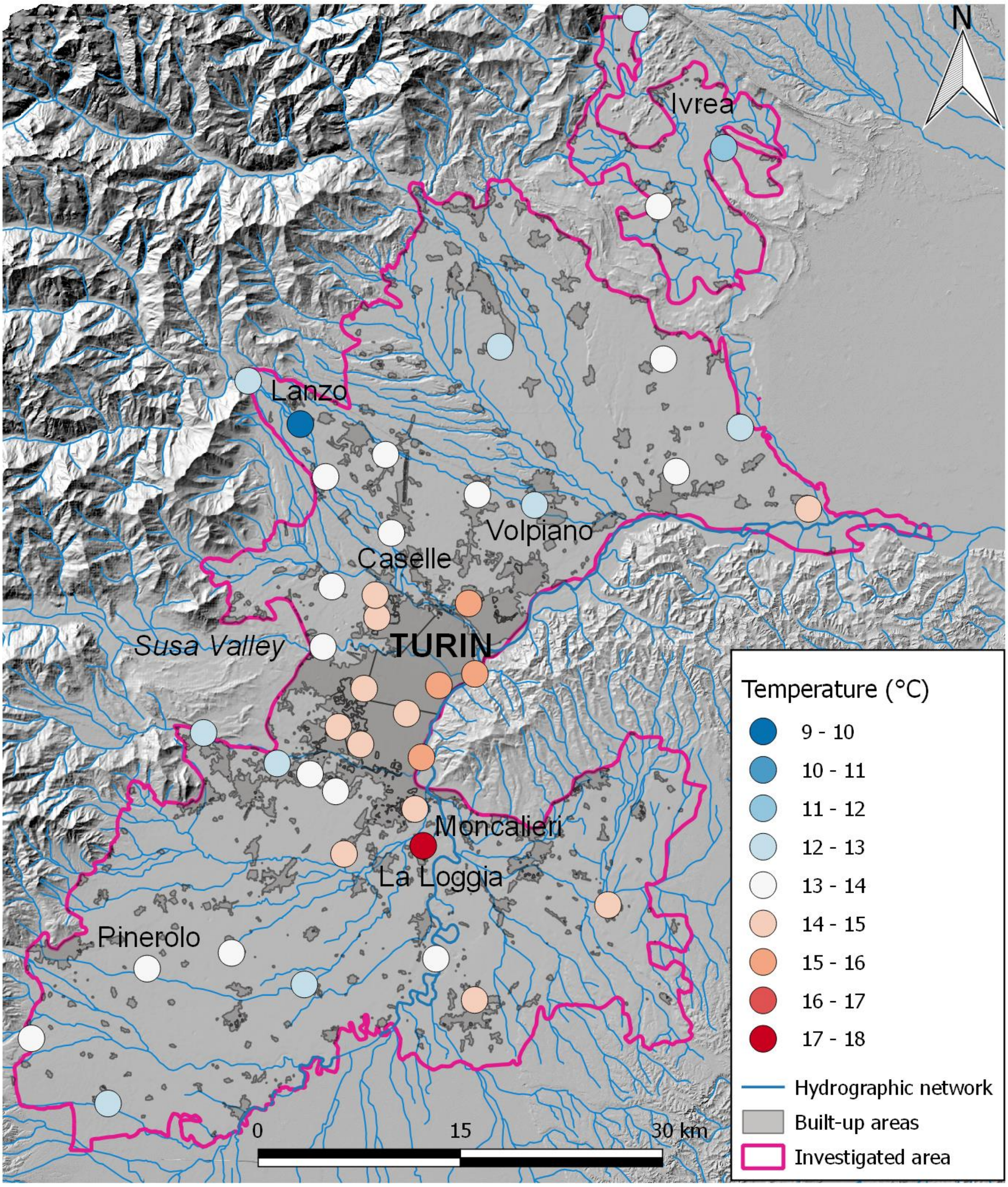

Fig. 7 Temperatures in the shallow aquifer in the spring of 2014. The plotted values refer to the well bottom temperatures.

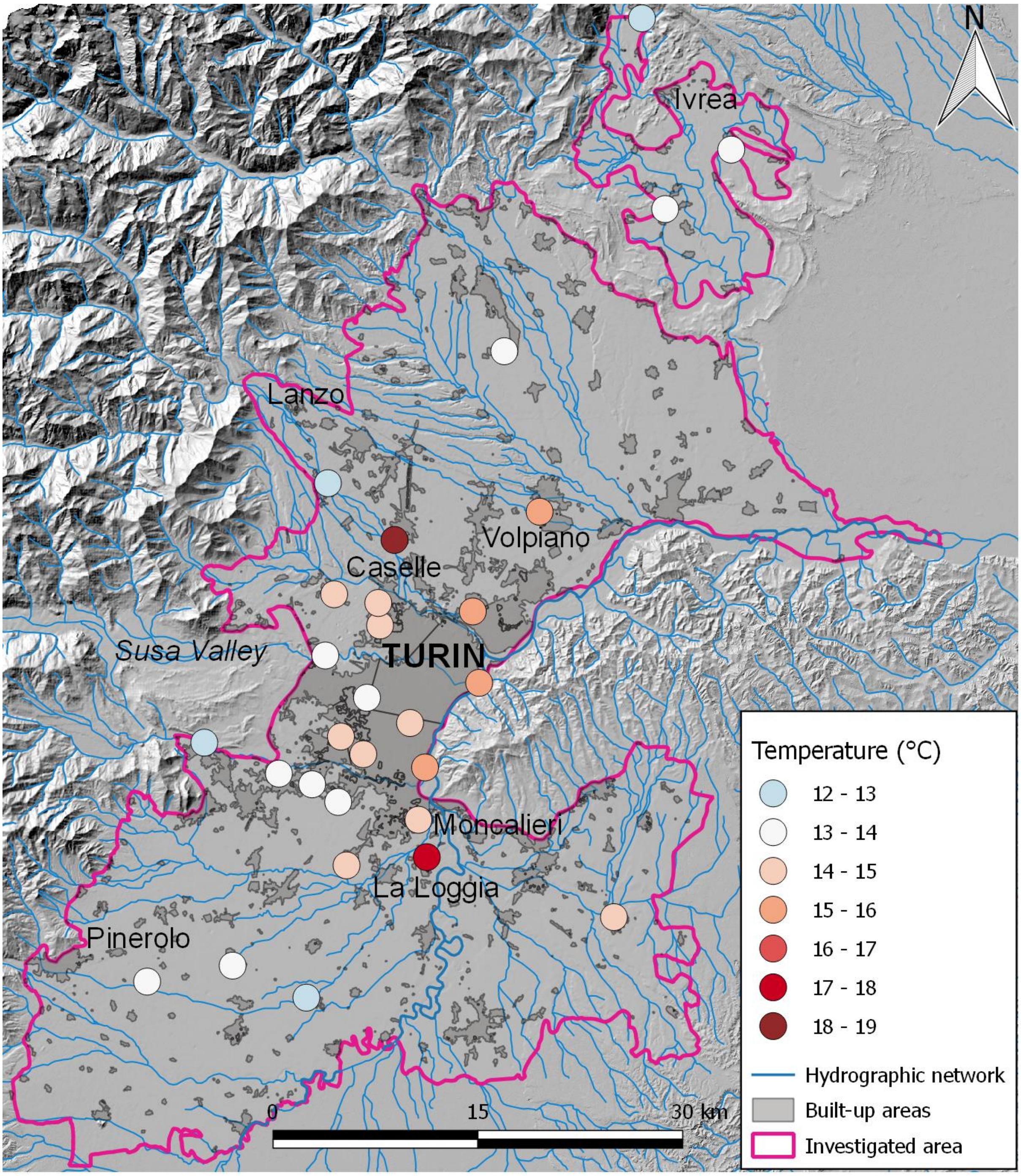

Fig. 8 Temperatures in the shallow aquifer in the autumn of 2014. The plotted values refer to the well bottom temperatures.